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Magnetospheric electron temperatures inferred from whistler observations at low latitudes

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Abstract Whistler observations during night times made at low latitude Indian ground stations Jammu (geomag lat 22° 26′ N, L = 1 17), Nainital (geomag lat , 19° 1′ N, L = 1 16) and Varanasi (geomag lat , 14°55′ N, L = 1 11) are used to deduced electron temperatures in the vicinity of the magnetospheric equator The accurate curve fitting and parameter estimation technique are used to compute nose frequency and equatorial electron densities from the dispersion measurements of short whistlers recorded at Jammu, Nainital and Varanasi These computed parameters are further used to estimate the magnetospheric electron temperatures from the dispersion analysis of short whistlers observed at low latitudes which are in good agreement with the results reported by other workers

Keywords Whistlers, electron temperature, magnetospheric equator, curve fitting technique

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1. Introduction

Whistler studies in India, which have been in progress since 1963, have made significant contribution to the propagation of low latitude whistlers and understanding of the structure and dynamics of the low latitude ionosphere [1-6] Recently, a coordinated whistler campaign was conducted at various low latitude Indian ground stations under All India Coordinated

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Program of Ionosphere Thermosphere studies (AICPITS) for the study on propagation mechanisms of low latitude whistlers and structure and dynamics of low latitude ionosphere During this campaign a large quantities of whistlers were acquired at our low latitude Indian ground stations. From the detailed dispersion analysis of whistlers collected during this campaign, the propagation mechanisms of low latitude whistlers are almost known, but the exploitation of whistler data collected in determining the magnetospheric parameters and other physical processes is very poor due to the demanding nature of analysis and limited available resources.

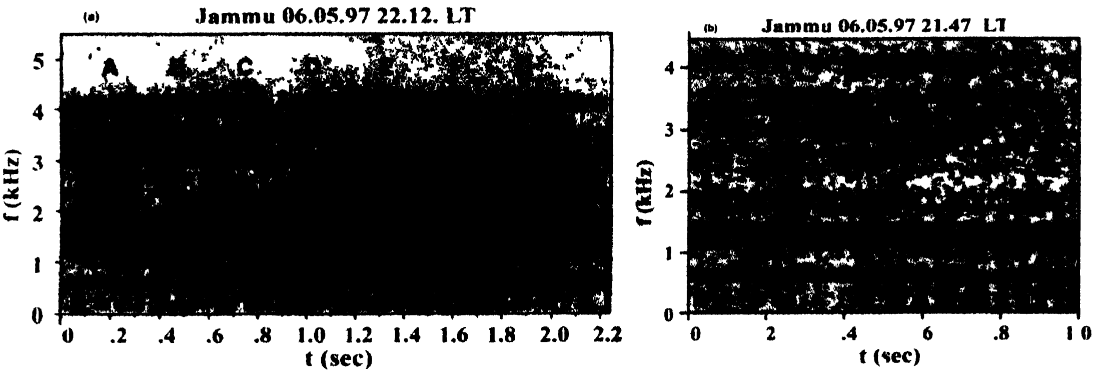
At middle and high latitudes both satellite and ground-based whistler data were exploited fully to reveal new facts about the structure and dynamics of the ionosphere and magnetosphere. These achievements included the discovery of the plasmasphere, plasmapause, and bulge [7], identification of the mechanisms of ionosphere-protonosphere coupling [8, 9] and the measurement of the magnetospheric electric field [10]. Although the application of whistlers to diagnostic of electron temperature at high latitudes has been discussed since the early 1960s [11-13], this problem still seems to be at an early stage of its development at low latitudes. Unfortunately, at low latitudes, whistler data have not been used for determining electron temperatures, the main reason being that the propagation paths of low latitude whistlers can not be determined from their dynamic spectra on frequency-time spectrograms, because the nose frequencies of such whistlers are higher than 100 kHz well above the pass band of the receiver and the frequency range of the sonogram. Such a nose frequency will have to be inferred by extrapolation techniques. For the analysis of non-nose whistlers, a number of methods have been proposed [14-19]. The nose frequency of the whistler data used in estimating electron temperature has been computed by means of accurate curve fitting method developed by Tarcsai [19] based on least squares estimation of the two parameters, zero frequency dispersion D_0, equatorial electron gyrofrequency f_{He} in Bernard's approximation. This matched filtering technique developed for the analysis of whistler waves increases the accuracy of analysis and speed of data processing [20-23, 4-6]. The technique employs dispersive digital filters whose frequency-time response is matched to the frequency-time response of the signal to the analyzed. Due to high resolution and time domain many fine structure components with amplitudes differing in frequency and time are seen in dynamic spectra [21, 22]. The accuracy and effectiveness of the technique have been discussed at length by analyzing a large number of whistlers both on the ground stations (from the low to the high latitudes) and onboard rockets/satellites [5-6, 21-25].

In the following we first present the whistler data used for the analysis recorded at Jammu, Nainital and Varanasi. This is followed by a presentation of the outline of the method developed by Tarcsai [19] from which electron temperatures in the vicinity of magnetospheric equator are evaluated. Finally the results are discussed and compared with those reported by other workers.

2. Data selection and method of analysis

At low latitudes, the whistler occurrence rate is low and sporadic But once it occurs, its occurrence rate becomes comparable to that of mid-latitudes [26] Similar behavior has also been observed at our low latitude Indian stations All the Indian stations are well equipped for measurements of VLF waves from natural sources For the present study, the whistler data chosen corresponds to June 5, 1997 for Jammu, 25 March 1971 for Nainital and 19 February 1997 for Varanasi On 5 June 1997 at Jammu station whistler activity started around 2140 h IST (Indian Standard Time) and lasted upto 2245h IST During this period about 100 whistlers have been recorded [5, 27] On 25 March 1971 at Nainital station whistler activity commenced around 0020 IST and lasted upto 0520 ISt Altogether more than hundred whistlers were recorded and the occurence rate showed a feeble but discernible periodicity [28] On 19 February 1997 at Varanasi station whistler activity started around 2300 IST and lasted for about one hour upto 0030 IST During this period several whistlers were recorded [23]

Figure 1(a) presents dynamic spectrum of short whistlers (marked A, B, C, D, E, F and G, selected for the analysis) in the frequency band 3-4 5 KHz recorded at Jammu at 2212 IST on June 5, 1997 In the frequency band 1 7-3 Khz large number of frequency components are missing and signals resemble more like emissions rather than whistlers Further, VLF waves in both the frequency bands do not appear simultaneously, rather they appear alternately Figure 1(b) shows dynamic spectrums of short whistlers (marked



(a) (b)

Figure 1. (a) Dynamic spectrum of whistlers recorded at Jammu June 5 1997 Whistlers are marked by A B, C, D, E, F and G and (b) Dynamic spectrum of whistlers recorded at Jammu June 5, 1997 Whistlers are marked by 1, 2, 3 and 4 (after Singh *et al* [5])

1, 2, 3 and 4, selected for the analysis) and VLF emissions recorded at Jammu at 2147 IST Whistlers are banded and diffused in the frequency range 2 7-3 7 Khz and are repeated in time The time interval between the events is not constant Unusual VLF noises are also seen in the spectrum Figure 2 shows dynamic spectrum of short whistlers selected for the analysis recorded at Nainital on March 25, 1971 The sonograms of sample whistlers (marked W1, W2, W3, W4 and W5) are arranged in a sequence for different time of arrival. Figure 3(a) and (b) shows the dynamic spectra of short whistlers (selected for analysis) recorded at Varanasi on 19 February 1997 at 0017 IST and 2338 IST respectively

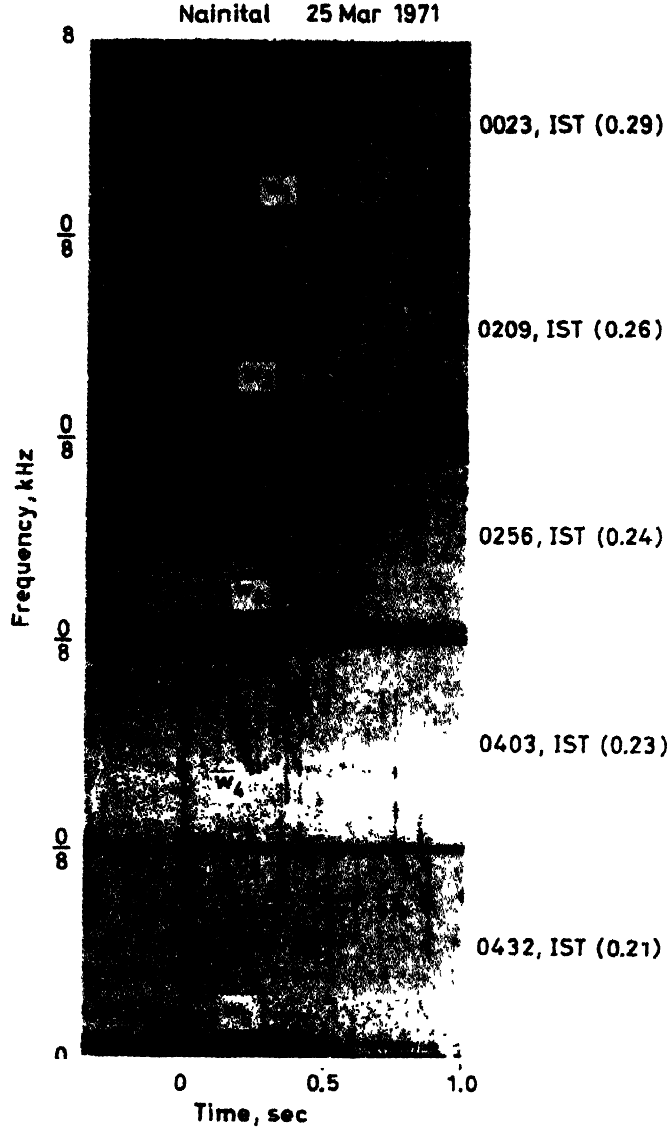


Figure 2. Dynamic spectrum of whistlers recorded at Nainital March 25, 1971, Whistlers are marked by W1, W2, W3, W4 and W5 (after Khosa *et al*, [42])

The whistlers are known to propagate along geomagnetic field lines in ducted mode The dispersion function under suitable approximation is written as [17]

$$D(f) = t(f)\sqrt{f} = D_0 \frac{(f_{He} - AF)}{(f_{He} - f)} \tag{1}$$

where D_0 is zero frequency dispersion, f_{He} is equatorial electron gyrofrequency, $t(f)$ travel time at frequency f, and

$$A = \frac{3\Lambda_n - 1}{\Lambda_n(1+\Lambda_n)}, \qquad \Lambda_n = \frac{f_n}{f_{He}} \tag{2}$$

f_n is the nose frequency for which travel time t_n is written as

$$t_n = \frac{2D_0}{\sqrt{f_n}}(1+\Lambda_n) \tag{3}$$

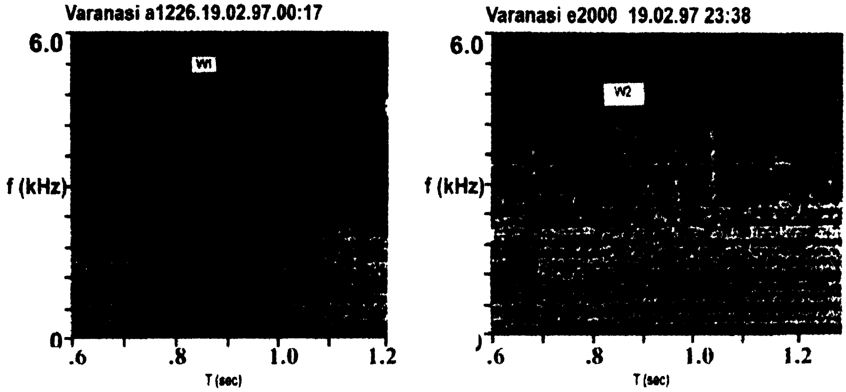


Figure 3. Dynamic spectrum of whistlers recorded at Varanasi, February 19, 1997 (after Singh *et al.* [23])

Sometimes the causative atmospherics is not known In such cases the travel time is measured from a chosen origin and a correction parameter T is introduced (which gives the time difference between the chosen origin and the actual sferic). Using eq. (1) and (2), the measured travel time $t^*(f)$ is written as

$$t^*(f) = t(f) - T = \left\{ \left(\frac{D_0 f_{He}}{\sqrt{f}\, f_n} \right) \frac{\left[f_n(f_{He} + f_n) - f(3f_n - f_{He}) \right]}{(f_{He} - f_n)(f_{He} + f_n)} \right\} - T \tag{4}$$

In this equation there are four unknown parameters D_0, f_{He} T and f_n. Tarcsai [19] has developed a computer program to solve eq. (4) for the unknowns using successive iteration method. In this method those values of D_0, f_{He}, T and f_n are searched which give best fit to the measured parameters. After Park [29] and using eq. (3) for t_n

$$t_n = 8.736 \times 10^5 \times f_{He}^{-1/3}, \quad \text{(where } f_{He} \text{ in Hz)}$$

$$n_{eq} = K_e\, f_n\, t_n^2\, L^{-5} = K'_e\, D_0\, f_{He}^{5/3} \tag{5}$$

$$N_T = K_T\, f_n\, t_n^2\, L^{-1} = K'_T\, D_0\, f_{He}^{1/3}$$

Where the constants K'_e and K'_T are weakly dependent on f_n and f_{He} [19]. Using eq. (5) and analyzing whistlers shown in Figure 1-3 recorded at Jammu, Naintal and Varanasi, nose frequency f_n, equatorial electron density n_{eq} and total electron content N_T in a flux tube of unit cross section has been evaluated. Then the equatorial electron temperature T_{eq} was estimated from nose frequency computed from Tarcsai [19] method for a given model of electron distribution for our analysis. A diffusive equilibrium model similar to that adopted by Park [29], Tarcsai [19], Chauhan and Singh [30] and Singh *et al* [5,6,22,23], was employed which was represented at the height 1000 km by an electron density 10^3 electron/cm^3, O+ = 90%, H+ = 8%, and He* = 2% at the temperature (T_{ref}) of 1000 °K The electron temperature in the magnetosphere (T_e) is related to the electron temperature at the reference level (T_{ref}) by the equation.

$$\frac{T_e}{T_{ref}} = \left(\frac{R}{R_{ref}}\right)^n \tag{6}$$

where R and R_{ref} are the corresponding geocentric distances. We took two values of n, (n = 1 and 2). For the case of n = 0, T_e remain almost constant and for the case of n = 2, T_e increases rapidly with height, one expect the actual value of n to lie between these two extremes. The results of the calculations of f_n, f_{He}, D_0, L, n_{eq} and T_{eq} for the whistlers under consideration are shown in Table 1 (for n = 1 and 2).

3. Results and discussion

Several attempts have been made to use whistlers as a diagnostic of the electron temperature of the magnetosphere besides the traditional methods of diagnostics of electron temperature in the magnetosphere. The first such attempt was probably made by Scarf [31] who estimated this temperature from the thermal attenuation of nose whistlers at the upper cut-off frequency. This method was developed by Liemohn and Scarf [32-34] but, to our knowledge, was never used in practice, perhaps for two reasons. Firstly, it is difficult to decide whether the whistler upper cut-off frequency is determined by wave attenuation or by propagation effects. Secondly, the interpretation of the whistler cut-off frequency in Scarf's method is very sensitive to the anisotropy of the electron distribution function, which can, in general, be determined only by *in situ* measurements.

In an alternative approach to this problem, McChesney and Hughes [35] measured the electron density at the magnetospheric equator (n_{eq}) by whistler dispersion analysis, and in the topside ionosphere from *in situ* observations of LHR noise. The ratio of these densities was fitted to a diffusive equilibrium model of electron density distribution with temperature as a parameter. The main assumption was that the electron temperature did not change along the magnetospheric magnetic field line. However, this assumption seems to be incompatible with satellite measurements of electron temperature-equatorial temperatures can be up to a factor of 10 larger than those at ionospheric altitudes [36, 37] and needs to be abandoned in further modifications of this method.

A different approach was taken by Guthart [38] who attempted to estimate magnetospheric electron temperature from its effect on whistler group velocity, assuming a gyrofrequency model electron distribution He predicted that the thermal effect on whistler spectra should be largest at frequencies near the upper cut-off frequency of nose whistlers However, the size of the effect was less than the experimental error associated with whistler spectral analysis This conclusion enabled Guthart to estimate an upper bound on the magnetospheric electron temperature of 2×10^4K ~ 1 7 eV By contrast, Kobelev and Sazhin [39] have argued that thermal effects in the vicinity of the plasmapause can be estimated by comparison of observed and theoretical whistler dispersion curves Assuming an electron density distribution along field lines, they obtained values of electron temperature in the range 7–19eV depending on the value of the parameter n This temperature corresponds to an average temperature of all electrons "cold" ones with energies $\leq$ 1 eV plus small "hot" components with energies of the order 1 keV In both these papers the effect of variation of the electron temperature along the magnetospheric magnetic field line was neglected as was done by McChesney and Hughes [35] More accurate analysis by Sazhin *et al* [40], based on the DE-1, 2, 3, 4 models described earlier, let to a result rather close to that of Guthart [38], namely, the magnetospheric electron temperature was estimated to be blow 4 eV and depends on the choice of electron distribution model

Sazhin *et al* [12] discussed different approaches to this type of diagnostic technique and have concluded that the most effective way to estimate the electron temperature with the help of ground – observed whistlers would be to use nose whistlers with the well-defined upper branch and compare whistler group delay times at the nose and at the upper cut-off frequency Recently, Sazhin *et al* [13] have extended this approach of analysis to a larger number of whistlers in order to get statistically more significant results They have shown that the estimated magnetospheric electron temperature strongly depends on the choice of model of electron distribution along the magnetospheric magnetic field line

The whistler data recorded at Jammu, Nainital and Varanasi at different times and for different magnetic activities have been analysid to estimate the magnetospheric electron temperature in the vicinity of magnetospheric equator at low latitudes We have applied the curve-fitting technique of Tarcsai [19] for our non-nose whistlers at these stations to derive the magnetospheric electron temperatures The results are shown in Table 1 The estimated temperature of magnetospheric electrons inferred from the whistler data shown in Table 1 is about 0 8 ev for the value of $n = 2$ and is about 0 25 eV for the value of $n = 1$ Our mean value of T_{eq} obtained using the diffusive equilibrium model estimated by the method of curve-fitting technique of Tarcsai [19] is ~ 0 5 eV, slightly smaller with other estimates of electron temperature in the equatorial plasmasphere [38,13,40,12] Magnetospheric temperatures are quite variable (e g Serbu and Maier [36] inferred temperatures between 5×10^3 K and 3×10^4 K, similar electron temperatures were deduced in a more detailed study by Decreau *et al* [41]) and it would be unwise to attempt to generalize our results

Table 1. Parameters of whistlers observed at Jammu, Nainital and Varanasi ground stations estimated from the whistler dispersion analysis using accurate curve fitting technique. *W* is the whistler number, IST is the Indian Standard Time, D_0 is the dispersion of whistler, f_n is the whistler nose frequency, f_{Heq} is equatorial gyro frequency, L-value is in earth's radii, n_{eq} is the equatorial electron density and T_{eq} is equatorial electron temperature.

W	Station	Dates & year	IST	D_0 ($sec^{1/2}$)	f_n (KHz)	f_{Heq} (KHz)	L Value	n_{eq} (cm^{-3})	n=1 T_{eq} (ev)	n=2 T_{eq} (ev)
1	Jammu	05 June 1997	21:40.25	65.5±1.0	4.2±0.03	11.37±0.07	4.25±0.01	159±3	0.28	0 85
2	Jammu	05 June 1997	21:47:42	81.9±1.1	3.39±0.013	10.59±0.034	4.35±0.005	220±5	0.29	0 86
3	Jammu	05 June 1997	22:47:50	88.9±1.8	3,82±0.02	10.27±0.05	4.39±0.07	247±8	0.29	0.87
4	Jammu	05 June 1997	22:47:55	87.6±1.4	3.85±0.01	10.37±0.03	4.38±0.00	244±6	0.29	0 87
5	Jammu	05 June 1997	22:12:20	28.8±1.2	8.15±0.72	21.98±1.95	3.41±0.10	93±6	0.20	0 4
6	Jammu	05 June 1997	22:12:51	28.9±0.9	6.29±8.21	16.96±0.55	3.72±0.04	61±1	0.14	0.5
7	Jammu	05 June 1997	22:13:22	35.5±1.7	6.13±0.25	16.51±0.66	3.75±0.05	88±2	0.24	0 6
8	Jammu	05 June 1997	22:13:53	38.3±1.9	4.61±0.10	12.42±0.28	4.12±0.03	63±4	0.27	0 7
9	Jammu	05 June 1997	22:14:24	26.1±0.6	5.76±0.13	15.53±0.35	3.83±0.02	43±4	0.25	0 6
10	Jammu	05 June 1997	22:14:55	22.8±1.7	5.99±0.41	16.17±1.10	3.78±0.08	35±1	0.24	0 5
11	Jammu	05 June 1997	22:15·26	38.9±1.2	5.06±0.09	13.62±0.24	4.00±0.02	76±3	0.26	0 6
12	Nainital	25 March 1971	00:23:00	20.2±2.1	68.33±0.0	204.45±0.84	1.62±0.00	298±0	0.05	0.2
13	Nainital	25 March 1971	02:09:00	18.6±0.6	16.85±3.0	45.9±0.82	2.67±0.00	136±3	0.14	0.2
14	Nainital	25 March 1971	02:56:00	18.5±0.9	9.72±1.1	26.2±0.381	3.21±0.00	52±6	0.19	0.3
15	Nanital	25 March 1971	04:03:00	13.2±0.7	13.24±2.6	35.8±0.72	2.89±0.00	45±1	0.1	0.2
16	Nainital	25 March 1971	04:32:00	15.4±0.5	8.53±3.9	23.0±0.10	3.36±0.00	29±1	0.2	0.4
17	Varanasi	19 Feb. 1997	00:17:00	11.9±0.3	36.8±2	103.5±60	2.1±0.4	247±24.6	0.1	0.2
18	Varanasi	19 Feb. 1997	23:38:00	13.5±0.2	13.1±1.1	35.3±31	2.9±0.01	45±5	0.1	0.2

4. Conclusion

The non-nose whistler recorded at Jammu [5,27], Nainital [28,42] and Varanasi [23] have been analysed to estimate the electron temperature at the equatorial magnetosphere. The estimated temperature is slightly smaller compared to the estimated value of other workers This preliminary test of our method of temperature diagnostic is rather encouraging However, before this method can be recommended for practical applications we need to be able to specify more accurately the model of electron density and temperature distribution in the magnetosphere, have a better estimate for the effect of ducted ray paths and increase the precision of determining whistler parameters

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